YAW INDUCED IN BULLET FLIGHT BY PASSAGE THROUGH FOLIAGE - INITIAL STUDY 7.62 mm BULLET

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Yaw Induced in Bullet Flight by Passage Through Foliage – Initial Study: 7.62 mm Bullet

J.D. Oliver and G.F. Whitty

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Abstract

It is found that as little as half a metre of foliage, lightly packed at a density typical of such vegetation, will induce vigorous and often irregular precessional motion in the 7.62 mm bullet, the yaw angle in some cases exceeding a right angle. Spaced 13 mm Caneite sheets induce a more regular and predictable precession that might be amenable to mathematical analysis, though much more data would be needed before analysis would be worth attempting. The yaw-measuring technique adopted is found to be capable of giving satisfactorily accurate results; the length of the path over which measurements can be taken is short, and this reduces the value of the data.

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Yaw Induced in Bullet Flight by Passage Through Foliage – Initial Study: 7.62 mm Bullet

1. *Introduction*

A spin-stabilized bullet flies with its long axis nearly co-incident with its trajectory unless disturbed by some unbalanced force. If such a disturbance occurs and an angle (the "yaw angle") develops between the axis of the bullet and the trajectory, a complicated motion called precession evolves in which the centre of mass of the bullet follows a linear trajectory while the nose of the bullet follows a spiral path, with possibly even more complex motions superimposed. Since the centre of pressure of a bullet lies ahead of its centre of mass, the effect of air resistance on a yawing bullet is a tendency to increase the yaw and hence to exacerbate the phenomenon; the stabilizing effect of spin will usually damp out the undesirable motion eventually, but while it continues the bullet experiences abnormally high air resistance and the trajectory becomes increasingly unpredictable.

If a bullet passes through a minor obstruction such as foliage, a series of small but cumulative disturbing forces is experienced. In small-arms fire over terrain covered with scrub, long grass, or rain forest, such impacts are very likely to occur, and an estimate of the extent of the resulting yaw and the nature of the precession is of value as a preliminary to an assessment of the battlefield consequences of the phenomenon. Some form of easily reproducible foliage simulant would be a useful experimental tool for this purpose, because an obstruction made from real foliage is not rigorously controllable from one shot to the next.

Aims

The aims of the experiments reported here were therefore to establish a technique for measuring the yaw induced in bullet flight by passage through a light foliage obstruction, to evaluate the use of spaced Caneite sheets as a foliage simulant, and to provide data on the yaw behaviour of standard 7.62 mm bullets. This calibre was chosen for the present series of experiments because the comparatively large size of the bullet makes it more visible on the flash x-ray film used to record the bullet attitude.

2. *Experimental Method*

Figure 1 shows the layout of the instrumentation. Standard 7.62 mm ammunition was fired from an Australian self-loading rifle (SLR) L1A1 supported in a Universal Gun Mount of Army manufacture. The bullet passed through an obstruction box placed approximately 23.5 m from the muzzle. The obstruction box was either filled with foliage or fitted with spaced sheets of Caneite; details of these various obstructions are given below. On emerging from the box the yawing bullet passed through the fields of two orthogonal banks of flash x-ray (FXR) tubes with four tubes in each bank; these tubes were triggered in pairs, one per pair from each bank, and the resulting images of the bullet were recorded on corresponding x-ray films together with reference marks which permitted the data from the two films to be scaled and correlated. A photo-electric detector screen was placed between the obstruction box and the FXR recording area to initiate the FXR triggering sequence; various time delays between initiation and triggering were chosen by experiment to give the four pairs of images a convenient spacing. The velocity with which the bullets arrived at the obstruction box, about 830 m/s, was measured with an MS Instruments projectile velocity measuring system which is not shown in Figure 1.

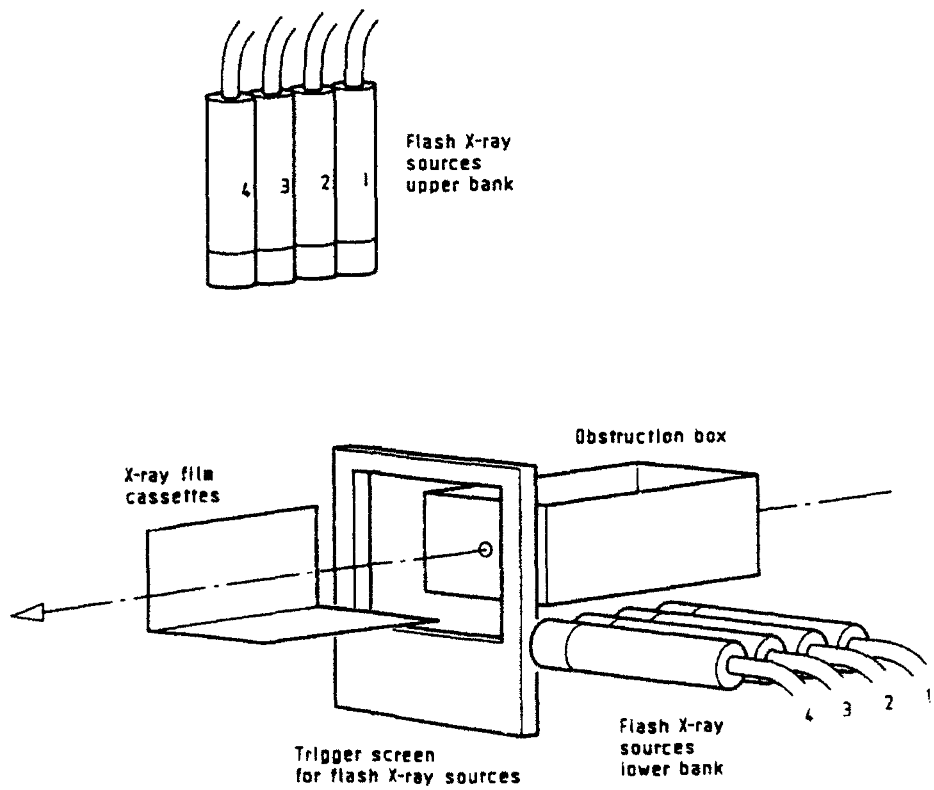


Figure 1: *Instrumentation.*

The FXR sources were position about 1.6 m from their associated film cassettes, and the shots were aimed to pass 80 mm above the horizontal film and 150 m to the left of the vertical film. The film images were thus only slightly enlarged. A sketch of a characteristic pair of film images is given in Figure 2. With the aid of the film reference marks the co-ordinates of the film images can be obtained and information such as yaw angle deduced. An approximate estimate of the bullet velocity can also be made.

For the initial sequence of eight shots, the obstruction was constructed of spaced sheets of 13 mm Caneite. This common wall-board material was included in the experiment to provide a standard and easily reproduced obstruction, and in the hope that comparison with the obstruction formed from real foliage would show it to be an adequate simulation material. The areal density of the Caneite used was 3.5 kg m^2. Figure 3 shows the spacing adopted.

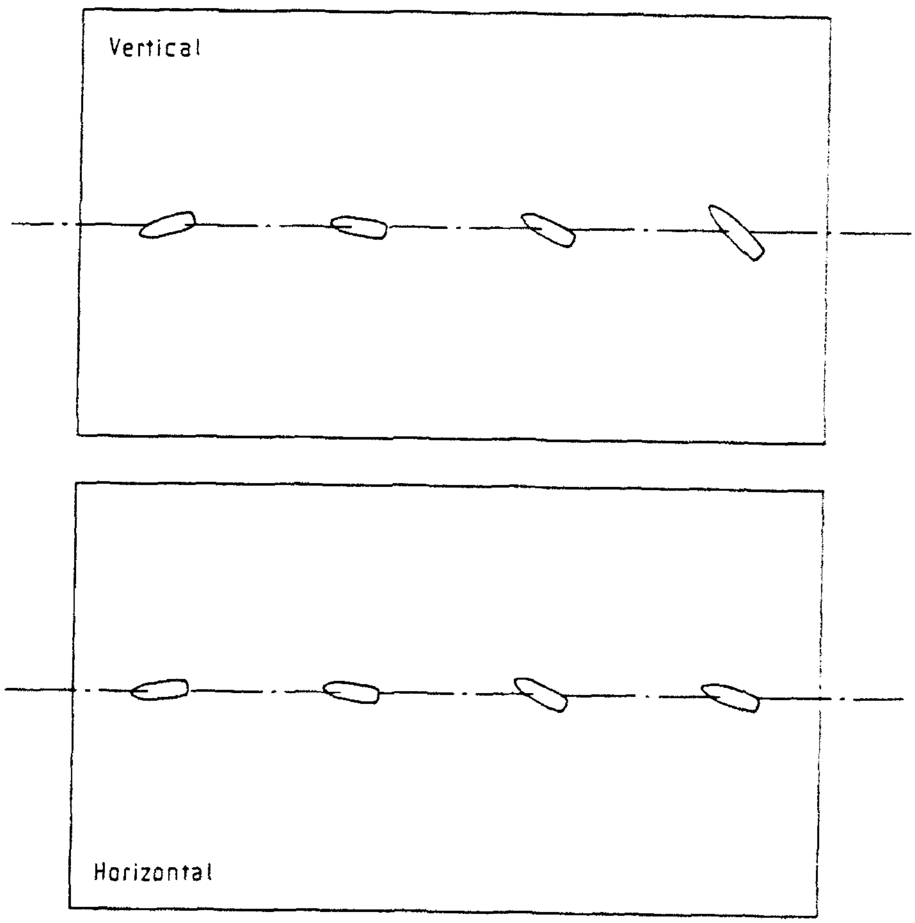


Figure 2: *Paired Film.*

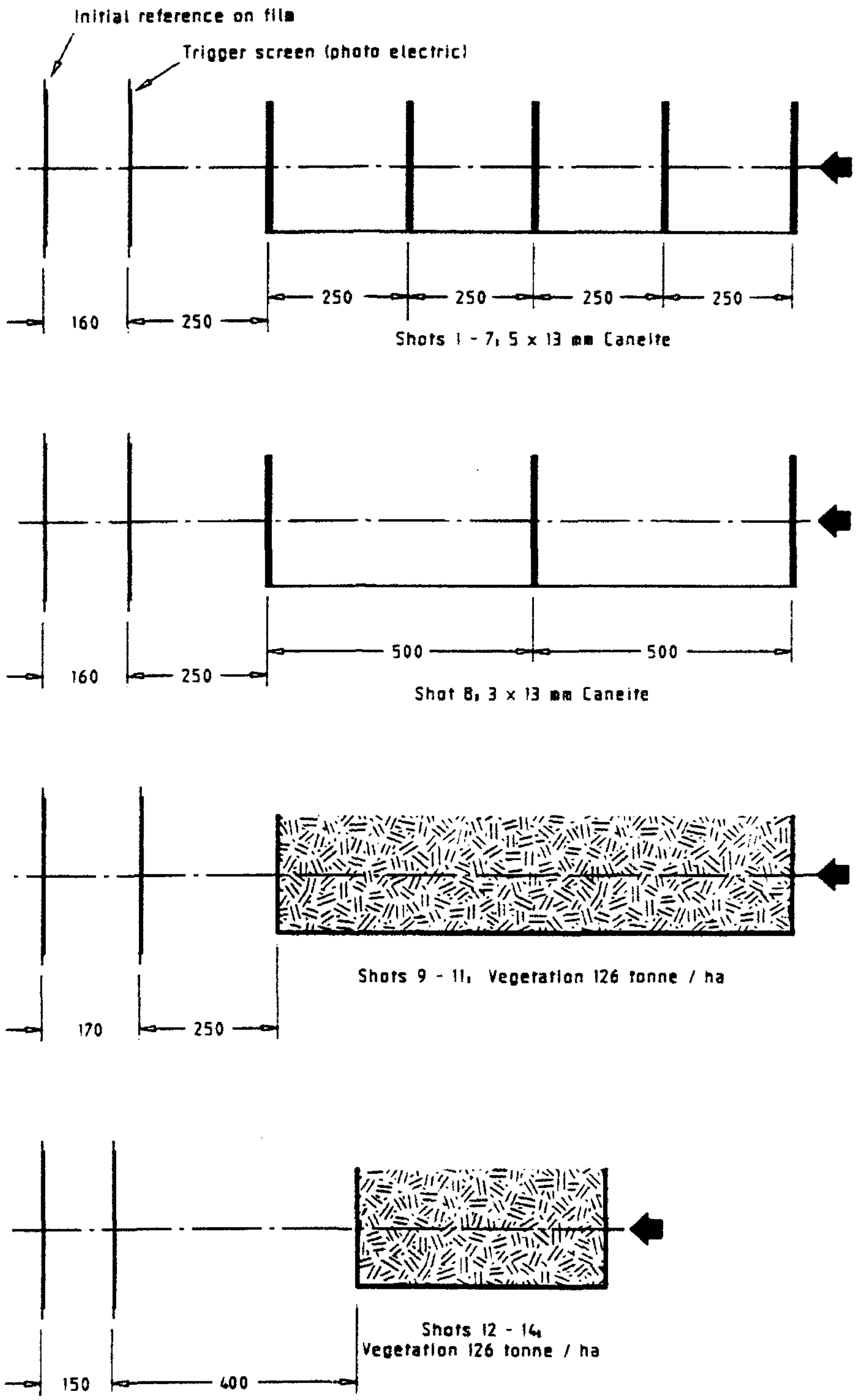


Figure 3: *Details of Obstruction and Spacing.*

In the second series of firings, fresh leaves and twigs from bushes round the firing range were used for the obstruction. The obstruction box, 0.5 m square on the face and usually 1 m long parallel to the line of fire, was loaded with 1.6 kg of fresh vegetation distributed as evenly as possible; this quantity was halved for the shorter (0.5 m) box used in the last two shots. The vegetation density, equivalent to 6.4 kg/m^3, was chosen as being typical of moderately dense scrub on the basis of biomass data reported by Minkoff [1969]; it is equivalent to 126 t/ha or 50 tons/acre in a layer 2 m high.

3. *Data Recovery and Interpretation*

Co-ordinate System

All positional data were recorded with reference to the three-dimensional co-ordinate system sketched in Figure 4. The chosen origin was the point at which the vertical from the first source in the upper FXR bank met the horizontal film. The horizontal down-range direction from this point was defined as the Y axis, the vertical as the Z axis, and the X axis (as required by a right-handed system) directed to the right as viewed by the firer, i.e. towards the vertical film. In this system, the horizontal film is part of the XY plane and the vertical film is parallel to the YZ plane; it is therefore easy to transform measurements taken from the films into the system co-ordinates. The co-ordinates of the eight FXR sources are also known, the two banks being parallel with the Y axis and having constant X and Z co-ordinates within each bank.

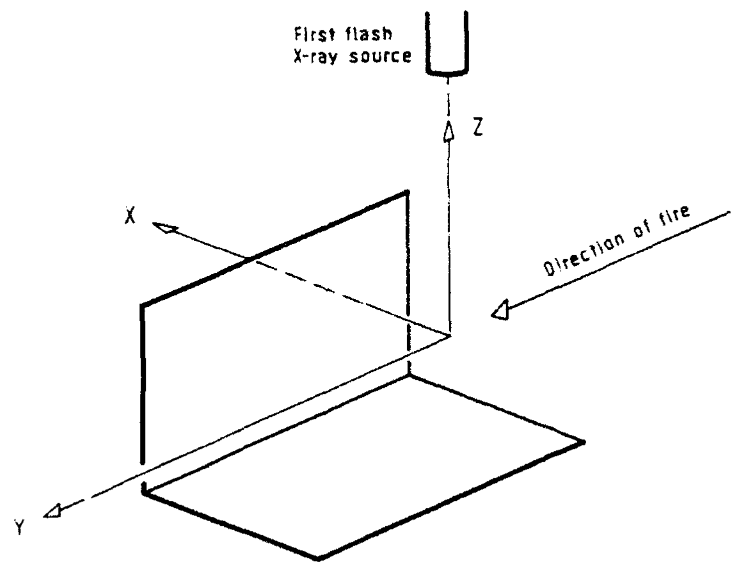


Figure 4: *Co-ordinate Axes.*

Data Recovery

For most film images, the data collected were the co-ordinates of the bullet nose, the centre of the base, and the centre of mass. This latter point is of course not defined on the image, and was estimated from a visual comparison of the image with an appropriately oriented scale diagram of the bullet on which the position of the centre of mass was marked. The successive positions of the centre of mass define the bullet path or trajectory, and it had been intended to measure yaw with reference to this trajectory; however, it was found that the typical path was parallel to the Y axis or nearly so, and it was decided to accept the angle between the axis and the bullet axis as being the yaw. (The error involved in this approximation is here always less than five degrees and is usually insignificant compared with other experimental errors). The centre-of-mass data were nevertheless useful in estimating the speed of the bullet after passage through the obstruction, which was usually in the region 750 to 790 m/s.

The path length over which FXR images were obtained was about 420 mm; the elapsed time between first and fourth FXR flash was about 0.55 ms.

Bullet Position

The procedure for calculating the co-ordinates of a point in space from the co-ordinates of its FXR image is as follows. In Figure 5, the point $A(x, y, z)$ is imaged by a source $P(x_1, y_1, z_1)$ at a location $I(x_2, y_2, z_2)$ on the film. The line from P to I has direction angles α, β, γ, where in the usual notation

$$\cos\alpha = (x_2 - x_1) / D, \quad \cos\beta = (y_2 - y_1) / D, \quad \cos\gamma = (z_2 - z_1) / D,$$

and D, the distance from source to image, is given by

$$D = [(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2]^{1/2}$$

(The direction angles of a line are defined in the usual way, by considering a line through the origin parallel to the given line, and taking the angles between the line and the three axes as the direction angles of the line. The customary notation α, β, γ, is adopted for the angles measured from the X, Y and Z axes respectively.)

If the direction cosines are written as

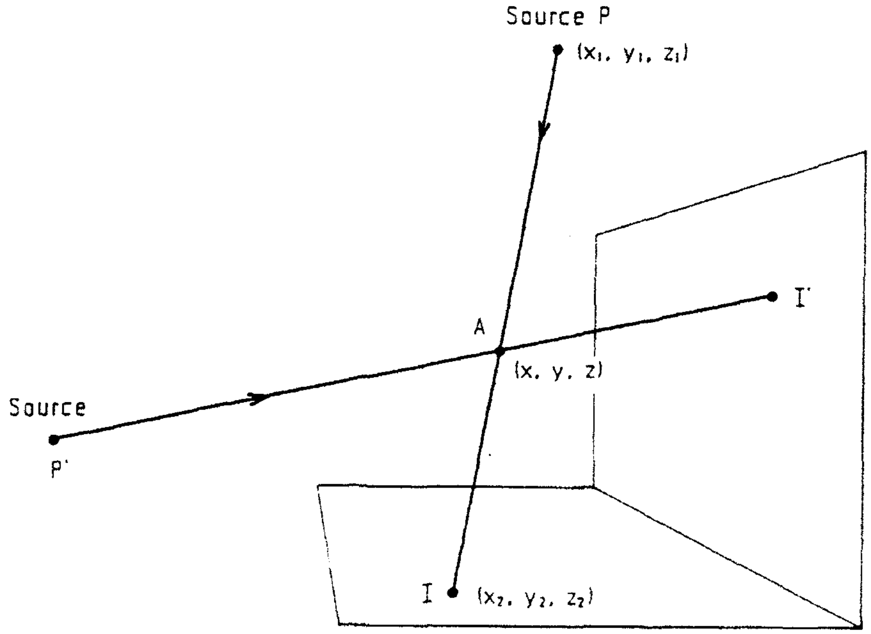
$$\cos\alpha = L, \quad \cos\beta = M, \quad \text{and } \cos\gamma = N,$$

then any point (x, y, z) on the line PI has co-ordinates given in parametric form as

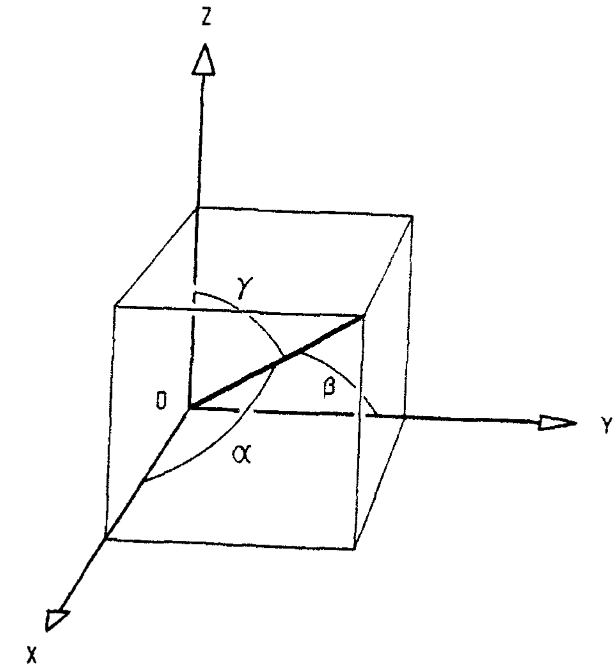
$$x - x_1 = \rho L, \quad y - y_1 = \rho M, \quad z - z_1 = \rho N,$$

where ρ is the parameter. For a second line $P'I'$ passing through A, similarly

$$x' - x_1' = \rho' L', \quad y' - y_1' = \rho' M', \quad z' - z_1' = \rho' N'.$$



(a)



(b)

Figure 5: Calculation of co-ordinates of the bullet

In an ideal world the two lines PI and $P'I'$ would indeed pass through point A. More usually, experimental data produce a near miss; the assumption made in this work is that the best estimate of A is the mid-point of the shortest line joining PI and $P'I'$. This estimate is made as follows.

Let the square of the distance between the general points (x, y, z) on PI and (x', y', z') on $P'I'$ be $S(\rho, \rho')$, i.e.

$$S(\rho, \rho') = (x - x')^2 + (y - y')^2 + (z - z')^2.$$

Now

$$x - x' = (\rho L + x_1) - (\rho' L' + x_1') = \rho L - \rho' L' + \delta x_1$$

where

$$\delta x_1 = x_1 - x_1', \text{ a constant term.}$$

Let δy_1 and δz_1 be similarly defined. Then partial differentiation of S with respect to ρ and ρ' yields

$$\partial S / \partial \rho = 2L(\rho L - \rho' L' + \delta x_1) + 2M(\rho M - \rho' M' + \delta y_1) + 2N(\rho N - \rho' N' + \delta z_1),$$

$$\partial S / \partial \rho' = -2L'(\rho L - \rho L' + \delta x_1) - 2M'(\rho M - \rho' M' + \delta y_1) - 2N'(\rho N - \rho N' + \delta z_1)$$

Equating the partial derivatives to zero gives

$$\rho(L^2 + M^2 + N^2) + \rho'(LL' + MM' + NN') + L\delta x_1 + M\delta y_1 + N\delta z_1 = 0$$

$$\rho(LL' + MM' + NN') + \rho'(L^2 + M^2 + N^2) + L'\delta x_1 + M'\delta y_1 + N'\delta z_1 = 0$$

From the definition of L, M and N it follows that

$$L^2 + M^2 + N^2 = 1, \quad L'^2 + M'^2 + N'^2 = 1.$$

Write

$$B = LL' + MM' + NN',$$

$$C = L\delta x_1 + M\delta y_1 + N\delta z_1,$$

$$C' = L'\delta x_1 + M'\delta y_1 + N'\delta z_1.$$

Then the equations giving the extremum are

$$\begin{cases} \rho - B\rho' + C = 0 \\ B\rho - \rho' + C' = 0 \end{cases}$$

Solved simultaneously, these yield

$$\rho = \frac{C'B - C}{1 - B^2} \quad ; \qquad \rho' = \frac{C' - CB}{1 - B^2}.$$

If the lines are truly orthogonal, $B = 0$; consequently these parameters are approximately $\rho = -C$, $\rho' = C'$.

Since $x = \rho L + x_1$ etc. the co-ordinates of the points on the two lines where the lines are at a minimum separation can be calculated directly from ρ, ρ' and the given co-ordinates for P, I, P' and I'. The co-ordinates of A are then easily obtained.

The co-ordinates of the various nose, base and centre-of-mass positions were deduced by this method and a small systematic error detected which could be explained by postulating a misplacement of the reference marks on either film; adding 3 mm to the Y co-ordinates of data from the vertical film reduced the bias significantly and the remaining calculations were performed on the adjusted data, although in fact the change had little effect on the yaw estimates.

Direction Angles and Yaw

The method of deducing the yaw from the co-ordinate data is based on the following principle. The co-ordinates of an FXR source and of any two distinct points on the axis of the corresponding image (such as the nose and the centre of the base) define a plane in space. The intersection of the two planes arising from an FXR pair is coincident with the bullet axis and has the same direction angles, which may be calculated by the method given below. As already discussed, the angle β is taken to be the yaw angle.

Let x_i, y_i, z_i (i = 1, 2, 3) be the co-ordinates of the three points defining the plane. The equation of the plane may be written in determinant form as

$$\begin{vmatrix} x & y & z & 1 \\ x_1 & y_1 & z_1 & 1 \\ x_2 & y_2 & z_2 & 1 \\ x_3 & y_3 & z_3 & 1 \end{vmatrix} = 0$$

or alternatively as

$$Ax + By + Cz + D = 0$$

where

$$A = \begin{vmatrix} y_1 & z_1 & 1 \\ y_2 & z_2 & 1 \\ y_3 & z_3 & 1 \end{vmatrix}, \quad B = \begin{vmatrix} z_1 & x_1 & 1 \\ z_2 & x_2 & 1 \\ z_3 & x_3 & 1 \end{vmatrix}, \quad C = \begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}.$$

As there are two such planes there are two sets of values A_j, B_j, C_j (j = 1, 2) which may be calculated from these equations; the direction components of the line of intersection of the planes are then calculated by means of the expressions

$$KL = \begin{vmatrix} B_1 & C_1 \\ B_2 & C_2 \end{vmatrix}, \quad KM = \begin{vmatrix} C_1 & A_1 \\ C_2 & A_2 \end{vmatrix}, \quad KN = \begin{vmatrix} A_1 & B_1 \\ A_2 & B_2 \end{vmatrix}.$$

The unknown K, which is in effect a scale factor, may be eliminated by making use of the well known result that

$$L^2 + M^2 + N^2 = 1,$$

and the direction cosines L, M and N and hence the direction angles obtained.

In certain circumstances, which apply approximately in the work reported here, it is possible to obtain β directly from angular measurements made on the film. The condition is that the position and orientation of the bullet are such that its axis (prolonged if necessary) passes through a point at which the normals from the FXR sources to the film intersect orthogonally. Let the angles measured on the films between the axes of the images and the projections of the Y axes be θ_1 and θ_2. In this idealized case, if β does not exceed a right angle,

$$\tan^2\beta = \tan^2\theta_1 + \tan^2\theta_2.$$

If β exceeds a right angle, the angles θ should be measured from the negative-Y axis, the equation then giving the supplement of β, i.e. 180° - β. This equation was found to be a good approximation for the images obtained in the present work, and consequently may be made use of to provide rapid preliminary estimates or to act as a check against gross error in similar experiments. A further useful approximation is the fact that β is only slightly larger than the larger of the two θ values, where "larger" means "nearer to ninety degrees"; this follows from the rapid rate of increase of $\tan^2\theta$ with θ, the sum of the two functions on the right of the equation being easily dominated by the larger value.

Precession Angles

The angle ϕ (Figs 6 and 7), and its modified relative Φ called the precession angle in this report, are introduced as a basis for displaying the direction-angle data graphically. To an observer looking down-range along the trajectory parallel to the Y axis, i.e. essentially along the line of advance of the centre of gravity of the bullet, the tip or nose of the bullet would appear to be executing a clockwise spiral sometimes modified by superimposed nutation-like motions (Fig. 6). If the distance from centre of gravity to the nose is taken as unity then the co-ordinates of the nose relative to the centre of gravity are $\cos \alpha$ horizontally and $\cos \gamma$ vertically; the clockwise angle from the Z axis (vertically upwards) as shown in Figure 7, is

$$\tan \phi = \cos \alpha \,/\, \cos \gamma .$$

(This equation defines ϕ). The apparent length is $\sin \beta$; thus if the bullet were to pass through a yaw card at this point the signature would be tilted through an angle ϕ clockwise from the vertical and be $l.\sin \beta$ in length, where l is the bullet length.

In order to facilitate comparison between shots, in displaying the data the pattern of ϕ values from each shot has in effect been rotated bodily anticlockwise so that the first value appears on the positive Z axis. This has been achieved by taking the ϕ data for each shot and subtracting from each value the value of the first. This results in a modified value Φ of ϕ, called here the precession angle.

$$\Phi_i = \phi_i - \phi_1 \qquad i = 1, 2, 3, 4$$

Necessarily, $\Phi_1 = 0$.

4. Results

The main experimental results, i.e. the direction angles and precession angles, are given in Table 1; the data from Caneite firings are illustrated in Figure 8 and the foliage data in Figure 9.

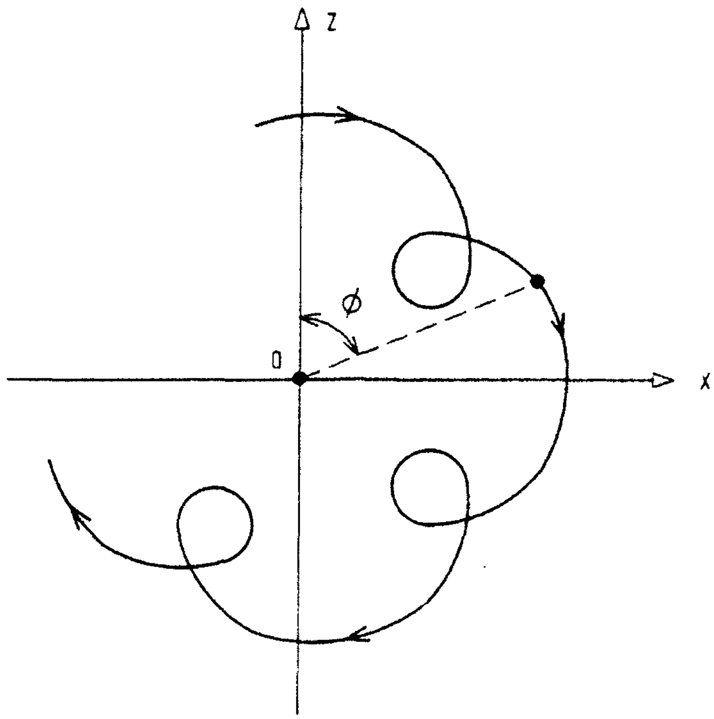


Figure 6: *Apparent motion of bullet tip as viewed from firing point.*

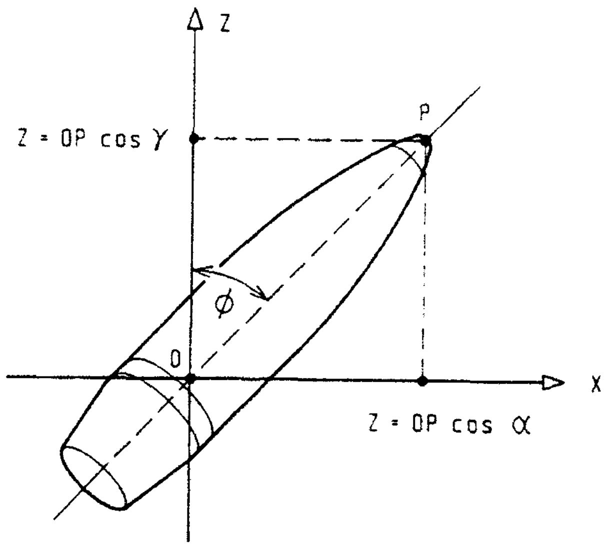


Figure 7: *Length OP projected on XZ plane has apparent length = sin β. The angle ϕ in this projected view is given by tan ϕ = cos α / cos γ.*

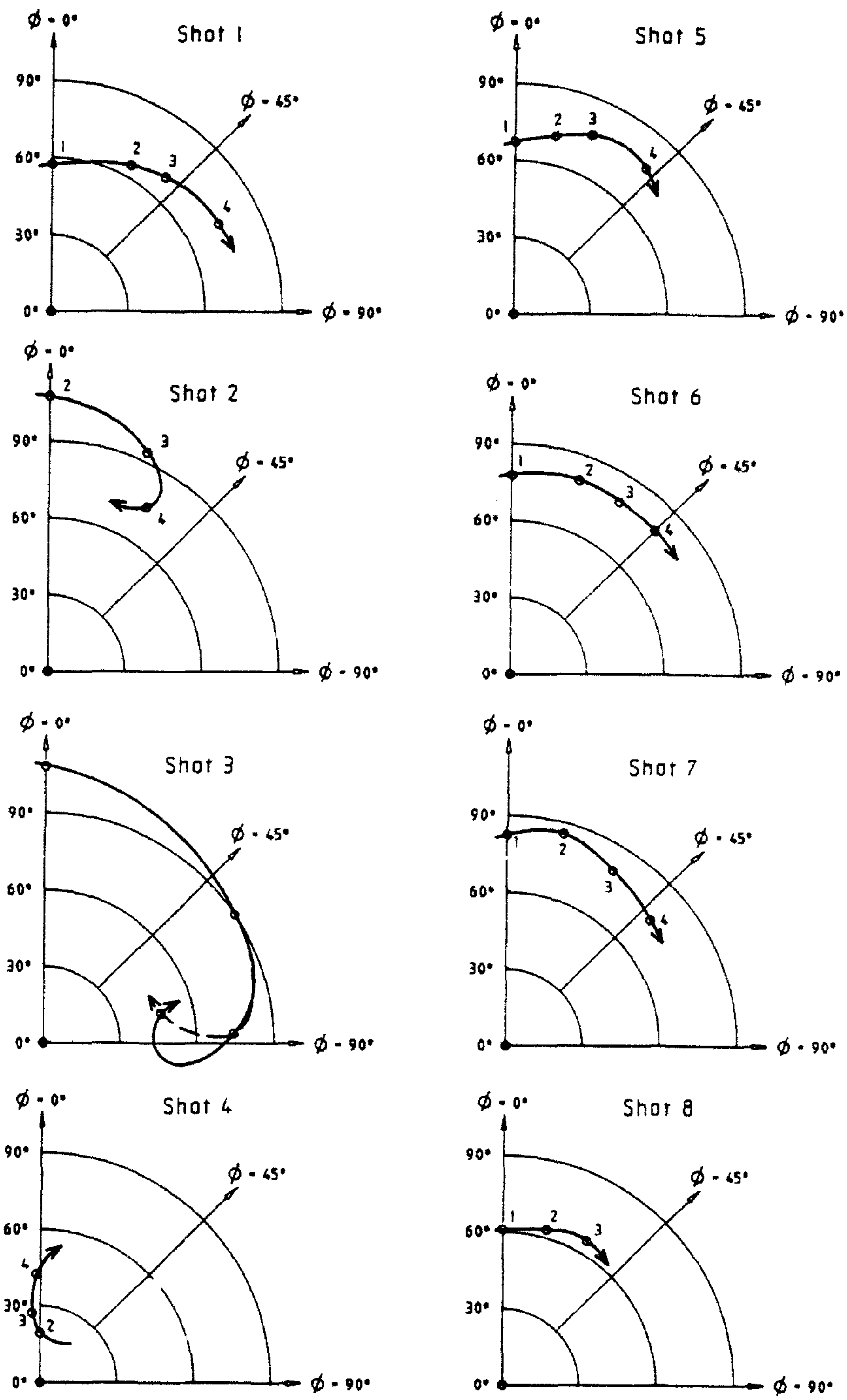


Figure 8: Caneite data.

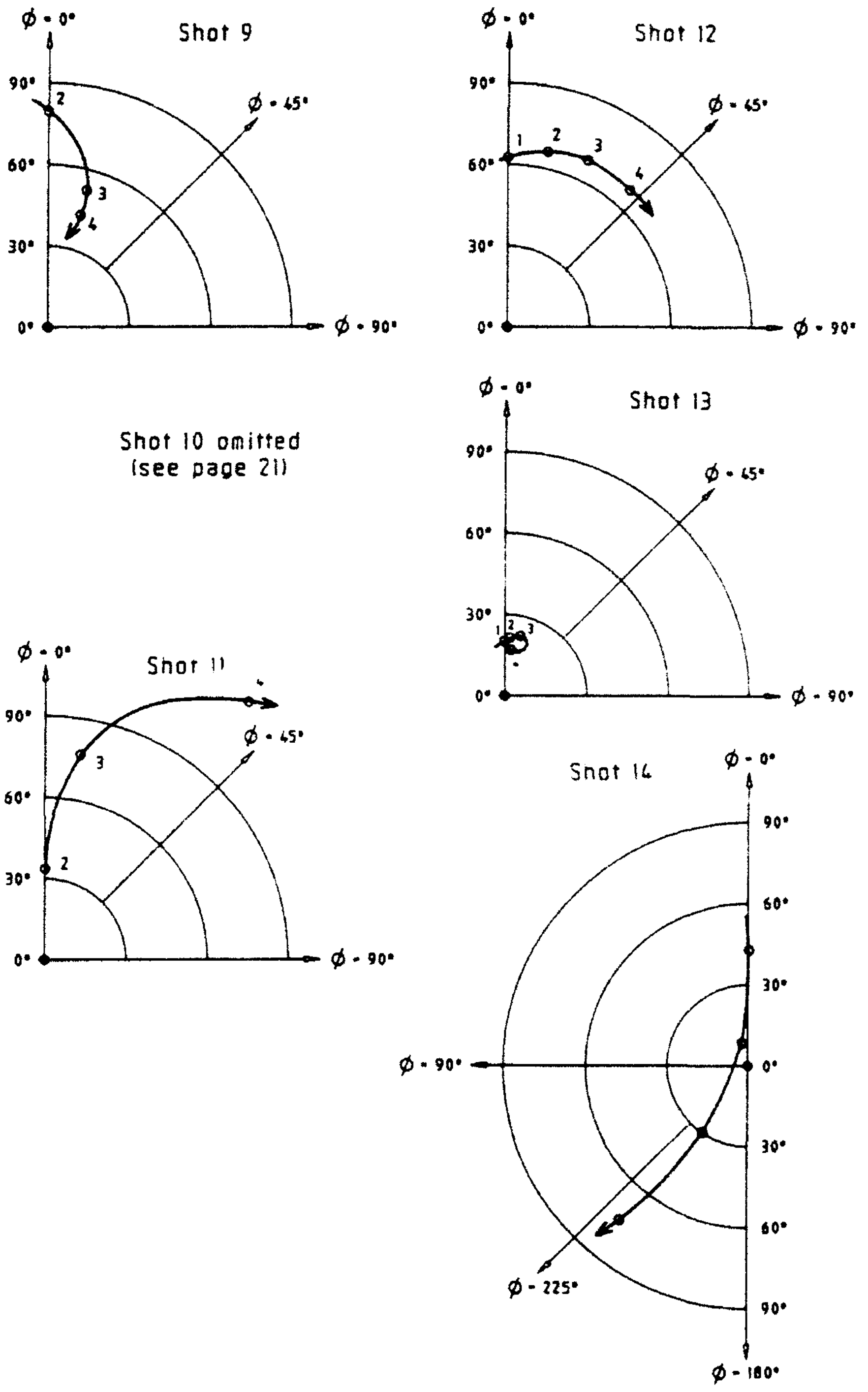


Figure 9: *Foliage data.*

Table 1: Direction Angles and Precession Angle of Bullet Axis

Shot Serial No.	FXR Delay No.	Direction Angles (deg)			Precession Angle (deg)	
		∝	β	γ	Φ	Φ
Shots through Spaced Caneite						
1	1	40.5	59.2	66.5	62.3	0
	2	24.1	65.9	90.5	90.5	28.2
	3	22.2	70.4	100.1	100.7	38.4
	4	35.8	76.0	122.2	123.4	61.1
2	2	95.1	107.1	162.1	185.3	0
	3	120.0	92.9	149.8	210.0	24.7
	4	125.5	75.6	140.8	216.8	31.5
3	1	25.4	107.1	108.2	109.0	0
	2	73.9	91.2	163.9	163.9	54.9
	3	103.6	74.0	158.8	194.2	85.2
	4	91.6	46.3	136.2	182.2	73.2
4	2	78.8	18.6	75.3	37.4	0
	3	76.9	27.3	66.4	29.5	352.1
	4	68.2	43.0	55.1	33.0	355.6
5	1	86.6	67.5	157.2	176.3	0
	2	98.2	73.3	161.3	188.6	12.3
	3	108.9	78.6	157.7	199.3	23.0
	4	126.3	77.5	140.9	217.3	41.0
6	1	51.9	79.6	140.0	141.1	0
	2	70.1	83.4	158.9	159.9	18.8
	3	82.0	81.0	167.9	171.9	30.8
	4	95.3	80.2	168.8	185.3	44.2
7	1	118.0	83.3	30.0	331.8	0
	2	103.4	86.1	14.0	346.6	14.8
	4	71.4	75.0	24.3	19.3	47.5
8	2	148.5	61.1	101.5	256.9	0
	3	155.1	65.2	88.4	271.8	14.9
	4	151.6	66.3	75.3	286.1	29.2
Shots through foliage						
9	2	127.4	81.0	38.8	322.1	0
	3	107.8	52.7	42.8	337.4	15.3
	4	98.0	23.6	67.9	339.7	17.6
11	2	56.1	34.5	84.2	79.7	0
	3	13.2	76.9	89.8	89.8	10.1
	4	42.7	123.2	113.6	118.6	38.9
12	1	126.9	62.9	48.9	317.6	0
	2	116.7	67.0	36.6	330.7	13.1
	3	105.8	68.4	27.3	343.0	25.4
	4	90.9	68.0	22.0	359.0	41.4

Table 1 (Continued):

Shot Serial No.	FXR Delay No.	Direction Angles (deg)			Precession Angle (deg)	
		α	β	γ	ϕ	Φ
13	1	71.3	21.3	99.9	118.1	0
	2	71.6	22.0	101.6	122.6	4.5
	3	72.9	23.2	105.1	131.6	13.5
	4	75.1	18.6	101.0	126.6	8.5
14	1	46.4	43.9	85.6	83.7	0
	2	82.7	8.3	86.2	62.7	339.0
	3	116.6	30.8	75.5	299.2	215.5
	4	142.4	75.8	56.0	305.2	221.5

Several shots have only three instead of the expected four sets of data. This is usually because the first pair of FXRs was inadvertently set to trigger too early, and operated before the bullet was over the films. On one shot (No. 7) the attitude of the bullet at the third FXR position was so nearly normal to one film that its axis could not be discerned on the image; in Figure 8 the missing point has been inserted by interpolation. Shot No. 10 is omitted entirely: the bullet emerged from the obstruction significantly distorted, and selecting axial points on the images would have been a matter of guesswork.

In Figures 8 and 9 the (β, Φ) data are plotted in polar form with Φ, the precession angle, as the position angle, against β, representing the yaw angle, as radial distance. This method is quite successful in displaying the data. For example, the figure for Shot 1 (Fig. 8) shows that the bullet was first detected with a yaw of magnitude 59°; then with a yaw of magnitude 66° in a plane rotated 28° clockwise from the first; then with a yaw of 70° in a plane of 38° from the first; finally with yaw 76° in a plane rotated 61° from the first. Thus in an elapsed time of 0.55 ms and over a path length of 0.42 m the bullet has precessed through a clockwise angle of 61° with yaw magnitude increasing from 59° to 76°.

5. *Discussion*

The Caneite data of Figure 8 show more regularity than the foliage data and will be considered first. In Shots No. 5, 6, 7 and 8 the motion appears to be almost steady, with the magnitude of yaw not changing greatly during the period of observation and the bullet precessing smoothly through about half a right angle. Shot No. 8, which penetrated only three Caneite sheets instead of five, appears to fit easily into this pattern. In Shots No. 2, 3 and 4 the bullet appears to be executing a nutation-like loop. There is obviously a considerable difference between these figures but the family likeness is clear. The loops are quite large and are not more than half completed during the period of observation. In Shot No. 1 the bullet may be emerging from a loop.

It is not clear whether these data derive from five shots precessing smoothly and three shots with serious irregularities, or represent eight samples from a motion in which nutation-like loops are regularly recurring. The second alternative seems the more likely; if the bullet in fact spends about 1.1 ms precessing smoothly followed by 1.1 ms in a loop and so on, eight random observatins could quite reasonably be expected to give the observed pattern of four smooth segments, three parts of loops, and what appears to be a transitional stage. It would take a series of observations over a much longer path to clarify the motion in detail, in particular to determine how long it takes for stable repetitive motion to become established and eventually die out. The Caneite data do, however, show regularities that encourage belief in the potential success of such a program of work.

The firings through natural foliage (Fig. 9, Shots No. 9 to 14) show much more irregular behaviour. Shot No. 12 follows the same pattern as the Caneite shots, and Shot No. 9 seems to be executing part of a regular loop; but the tight loop in Shot No. 13, the wild swing to 123° yaw in Shot No. 11, and the sweeping motion in Shot No. 14, are all markedly different from the motion induced by Caneite. Explanations on the basis of such sparse data can only be speculative, but it seems possible that Shots No. 11 and 14 represent a kind of precession about an axis directed away from the bullet trajectory and presumably also undergoing a precession-like motion. The resources available for this work did not permit a greater number of shots and a longer downrange observation of the trajectories, from which a clearer idea of the very complex and varied motions could have been obtained.

6. *Conclusions*

The technique adopted for measuring the yaw of bullets in flight has performed well and is capable of producing estimates of yaw, precession and velocity of satisfactory accuracy.

Facilities permitting the extension of the field of observation to two or three times its existing size would markedly improve the value of the results obtainable.

An obstruction formed from spaced Caneite sheets provides a means of inducing a reasonably regular yaw and precession in 7.62 mm bullet flight. The use of such material as a foliage simultant could provide reliable data on which to base a mathematical analysis of the development of the complex motion observed; however, it is artificial in the sense that real foliage will induce phenomena of a much more varied nature.

The 7.62 mm bullet, though quite heavy and stable in comparison with more recent 5.56 mm bullets, is caused to yaw vigorously by a surprisingly short passage through material which would have seemed likely to have little effect. The magnitude of the yaw can exceed 90°, and the associated motion is likely to continue for an appreciable distance along the trajectory.

7. Acknowledgement

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8. References

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Yaw induced in bullet flight by passage through foliage ~ Initial study: 7.62 mm bullet

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ABSTRACT

It is found that as little as half a metre of foliage, lightly packed at a density typical of such vegetation, will induce vigorous and often irregular precessional motion in the 7.62 mm bullet, the yaw angle in some cases exceeding a right angle. Spaced 13 mm Caneite sheets induce a more regular and predictable precession that might be amenable to mathematical analysis, though much more data would be needed before analysis would be worth attempting. The yaw-measuring technique adopted is found to be capable of giving satisfactorily accurate results; the length of the path over which measurements can be taken is short, and this reduces the value of the data.

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(MRL-TR-92-20)

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